Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 2 (2009) 113–119
Physics Procedia
www.elsevier.com/locate/procedia

Frontier Research in Nanoscale Science and Technology

A pulsed source of polarization-entangled photon pairs

Surasak Chiangga[a,] * and Kitisak Boonkham

[a]*Department of Physics, Faculty of Science, Kasetsart University, Bangkok, 10900, Thailand*
[b]*Mahidol Wittayanusorn School, Salaya, Buddhamonthon, Nakonpathom, 73170, Thailand*

Abstract

We report a Bell state preparation experiment using polarization-entangled photon pairs which are produced by spontaneous parametric down conversion of a 405 nm pulse laser beam inside two orthogonally oriented 0.1 mm beta-barium borate nonlinear crystals with Type-I phased matching. The degree and phase of all four Bell states are easily tunable. With two-photon interference visibilities in excess of 85%, we observe that the Bell parameter S for any of the four Bell states exceeds the classical limit in the Clauser-Horne-Shimony-Holt form of Bell inequality by five standard deviations.

PACS: 03.67.Bg

Keywords: Bell inequality; Entangled photon; Parametric down conversion; Nonlinear crystals; Polarization entanglement

1. Introduction

Entangled photon pairs play an important role in various quantum information experiments, such as quantum computation, quantum cryptography, quantum dense coding, and quantum teleportation [1]. In addition, entangled photon pairs are useful application in tests of Bell inequalities [2,3]. Thus, the efficient generation and manipulation of quantum entanglement is the most important. Recently, a compact entangle-photon source rely on spontaneous parametric down conversion in nonlinear crystals pumped by CW laser diode has made available to the undergraduate laboratories [4].

In this paper, we describe the preparation of all four orthogonal Bell states, relying on thin noncollinear two-crystal scheme type-I phase matching pumped by pulse beam of a violet diode laser. A detailed description of the down-conversion source used to produce and characterize the entangled photons is given. The joint photodetection probabilities and the Bell inequality in the Clauser-Horne-Shimony-Holt (CHSH) version are briefly discussed. The degree of polarization entanglement between photon pairs is experimentally verified by a violation of CHSH inequality.

* Corresponding author. Tel.: +662-942-8028; fax: +662-942-8029.
E-mail address: fscissc@ku.ac.th.(S. Chiangga)

doi:10.1016/j.phpro.2009.06.018

2. Setup

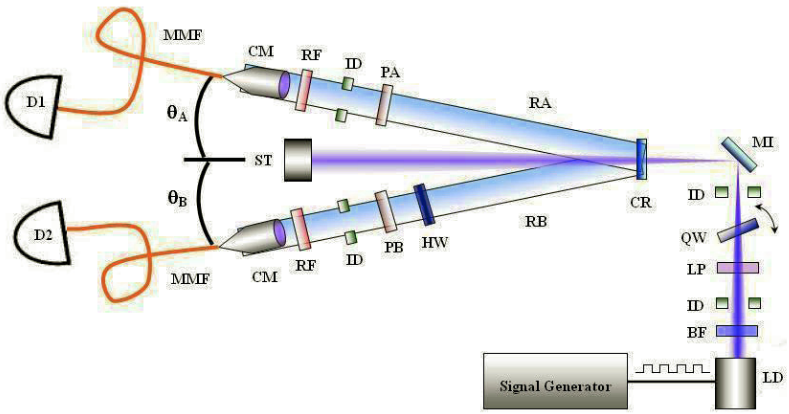


Fig. 1. Schematic of experimental setup, not to scale. Symbols: (LD) Laser Diode Module, (BF) Blue Filter, (ID) Iris Diaphragm, (LP) Laser Polarizer, (QW) Quarter-wave plate, (MI) Mirror, (CR) Downconversion Crystals, (RA) Rail A, (RB) Rail B, (PA) Polarizer A, (HW) Haft-wave plate, (PB) Polarizer B, (RF) Red Filter, (CM) Collimator, (MMF) Multimode Fiber, (D1) Detector 1, (D2) Detector 2, (ST) Beam Stop.

A schematic diagram of our experimental set up to produce polarization-entangled photons is shown in Fig. 1. The laser is a 60-mW, 405-nm laser diode module (Newport model LQA-405E). The output power of the laser is controlled by the square wave generator. With the control voltage of 1VDC and the repetition rate of 100 Hz, the diode laser produces pulse beam of 60 mW, 100 Hz (specified by the manufacturer). The beam of photons passes through a blue filter, a linear polarizer, and a zero order wave plate before reaching a pair of beta barium borate (BBO) crystals. A detailed description of a two-crystal geometry is given in [5]. In brief, the crystals are cut for type-I phase matching, and are aligned so that their optic axes lie in planes perpendicular to each other. The pump beam and optic axis of the first crystal define the vertical plane, that of the second crystal, the horizontal plane, as in Fig. 2. If the pump beam is vertically (horizontally) polarized, down-conversion occurs only in crystal 1 (crystal 2). When the pump polarization is set to 45°, it is equally to down-convert in either crystal [6]. Our BBO are 0.5×0.5×0.1 mm, and in contact face-to-face, optic axis cut at 28.5°. For this cut the degenerate-frequency photons at 810 nm are likely emitted in collinear cone. For the data present here, we tune the crystal to emit into a cone of haft-opening angle 2.5°. The down-converted photons produced in the BBO crystals travel about 1 m before passing an adjustable iris diaphragm, a near-infrared polarizer, a RG780 colored glass filter, and are collected by fiber collimators into multimode fibers which direct the photons to the commercial silicon APD single-photon detectors (Perkin-Elmer model SPCM-AQ4C). Coincidence counting is done using coincidence circuit described in [7]. We use a 25 ns coincidence window. Typical accidental coincidence rate are 10 Hz. The universal frequency counter (Stanford Research model SR620) does the counting.

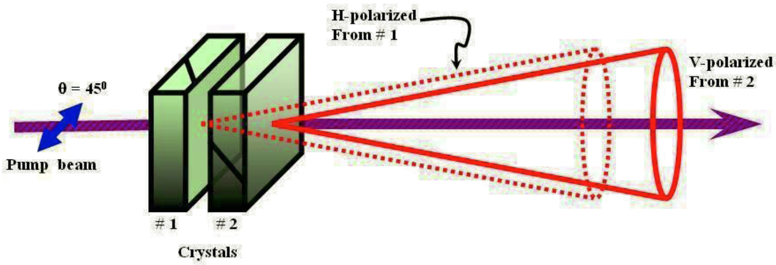


Fig. 2. Two-crystals down conversion source, not to scale. The crystals are 0.1 mm thick and in contact face-to-face, while the pump beam is approximately 1 mm in diameter. Thus the cones of down converted light from the two crystals overlap almost completely.

3. Joint Probability

Our BBO crystals are cut for Type I phase matching, which means that the signal and idler photons emerge with the same polarization, which is orthogonal to that of the pump photon. Each crystal can only support down-conversion of one pump polarization. The other polarization passes through the crystal unchanged. We use two crystals, one rotated 90° from the other, so that either pump polarization can down-convert according to the rules

$$\left|V\right\rangle_P \rightarrow \left|H\right\rangle_s \left|H\right\rangle_i \tag{1a}$$

$$\left|H\right\rangle_P \rightarrow \exp[i\Delta]\left|V\right\rangle_s \left|V\right\rangle_i \tag{1b}$$

where Δ is a phase due to dispersion and birefringence in the crystals. The geometry is shown schematically in Fig. 2.

To create an entangled state, we first linearly polarize the laser beam at an angle θ_ℓ from the vertical and then shift the phase of one polarization component by ϕ_ℓ with the quarter wave plate. The pump photons are then in the state

$$\left|\psi_{pump}\right\rangle = \cos\theta_\ell \left|V\right\rangle_p + \exp[i\phi_\ell]\sin\theta_\ell \left|H\right\rangle_p \tag{2}$$

when they reach the crystals. The down-converted photons emerge in the state

$$\left|\psi_{DC}\right\rangle = \cos\theta_\ell \left|H\right\rangle_s \left|H\right\rangle_i + \exp[i\phi]\sin\theta_\ell \left|V\right\rangle_s \left|V\right\rangle_i \tag{3}$$

where $\phi \equiv \phi_\ell + \Delta$ is the total phase difference of the two polarization components.

By placing polarizers rotated to angles α and β in the signal and idler paths, respectively, we measure the polarization of the down-converted photons. For a pair produced in the state $\left|\psi_{DC}\right\rangle$, the probability of coincidence detection is

$$P_{VV}(\alpha,\beta) = \left|\left\langle V_\alpha\right|_s \left\langle V_\beta\right|_i \left|\psi_{DC}\right\rangle\right|^2 \tag{4}$$

The VV subscripts on *P* indicate the measurement outcome $V_\alpha V_\beta$, both photons vertical in the bases of their respective polarizers. More generally, for any pair of polarizer angles α, β there are four possible outcomes, $V_\alpha V_\beta$, $V_\alpha H_\beta$, $H_\alpha V_\beta$ and $H_\alpha H_\beta$ indicated by VV, VH, HV and HH, respectively. We find

$$P_{VV}(\alpha,\beta) = \sin^2\alpha \sin^2\beta \cos^2\theta_\ell + \cos^2\alpha \cos^2\beta \sin^2\theta_\ell + \frac{1}{4}\sin 2\alpha \sin 2\beta \sin 2\theta_\ell \cos\phi \tag{5}$$

A special case occurs when $|\psi_{DC}\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_s |H\rangle_i + |V\rangle_s |V\rangle_i\right)$, i.e., when $\theta_\ell = \pi/4$ and $\phi = 0$. In this case

$$P_{VV}(\alpha,\beta) = \frac{1}{2}\cos^2(\beta-\alpha) \tag{6}$$

which depends only on the *relative* angle $\beta - \alpha$.

Because the laser has a finite linewidth and we collect photons over a finite solid angle and wavelength range, we collect a range of ϕ. To account for this, we replace $\cos\phi$ in Eq. (5) by its average $\langle\cos\phi\rangle = \cos\phi_m$ to get

$$P_{VV}(\alpha,\beta) = \sin^2\alpha \sin^2\beta \cos^2\theta_\ell + \cos^2\alpha \cos^2\beta \sin^2\theta_\ell + \frac{1}{4}\sin 2\alpha \sin 2\beta \sin 2\theta_\ell \cos\phi_m \tag{7}$$

In our experiment we choose a fixed interval *T* of data acquisition (typically in the range 0.1 s to 10 s) and record the number of coincidences $N(\alpha, \beta)$ during that interval. Assuming a constant flux of photon pairs, the number collected will be

$$N(\alpha,\beta) = A(\sin^2\alpha \sin^2\beta \cos^2\theta_\ell + \cos^2\alpha \cos^2\beta \sin^2\theta_\ell + \frac{1}{4}\sin 2\alpha \sin 2\beta \sin 2\theta_\ell \cos\phi_m) + C \tag{8}$$

where *A* is the total number of entangled pairs produced, and *C* is an offset to account for imperfections in the polarizers and alignment of the crystals. This offset is necessary to account for the the fact that some coincidences are observed even when the polarizers are set to $\alpha = 0^\circ$, $\beta = 90^\circ$.

4. The Bell Inequality

The Bell inequality constrains the degree of polarization correlation under measurements at different polarizer angles. The proof involves two measures of correlation. The first is

$$E(\alpha,\beta)=\frac{N(\alpha,\beta)+N(\alpha_\perp,\beta_\perp)-N(\alpha,\beta_\perp)-N(\alpha_\perp,\beta)}{N(\alpha,\beta)+N(\alpha_\perp,\beta_\perp)+N(\alpha,\beta_\perp)+N(\alpha_\perp,\beta)} \tag{9}$$

The second measure is

$$S \equiv E(a,b)-E(a,b')+E(a',b)+E(a',b') \tag{10}$$

where $a,\ a',\ b,\ b'$ are four different polarizer angles. *S* does not have a clear physical meaning. Its importance comes from CHSH proved [8]

$$|S| \le 2 \tag{11}$$

for any local realistic theory and arbitrary $a,\ a',\ b,\ b'$. Quantum mechanics can, for certain settings, violate this inequality. If we choose the polarizer angles, $a=0^\circ$, $a'=45^\circ$, $b=22.5^\circ$ and $b'=67.5^\circ$, using Eqns. (6), (9), and (10),

$$S^{(QM)}=2\sqrt{2} \tag{12}$$

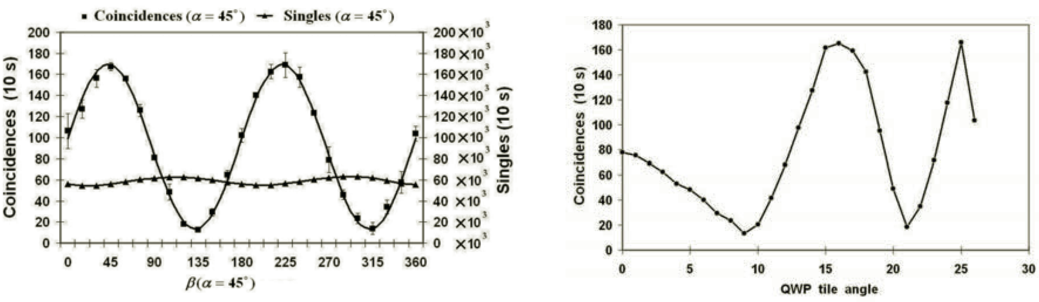
This result is specifically to any of the four Bell states,

$$\left|\psi^\pm\right\rangle=\frac{1}{\sqrt{2}}\left(\left|H\right\rangle_s\left|V\right\rangle_i \pm \left|V\right\rangle_s\left|H\right\rangle_i\right) \tag{13a}$$

$$\left|\phi^\pm\right\rangle=\frac{1}{\sqrt{2}}\left(\left|H\right\rangle_s\left|H\right\rangle_i \pm \left|V\right\rangle_s\left|V\right\rangle_i\right) \tag{13b}$$

which form the complete maximally entangled basis of the two-particle Hilbert space. Other states give lower values of *S*.

5. Verification

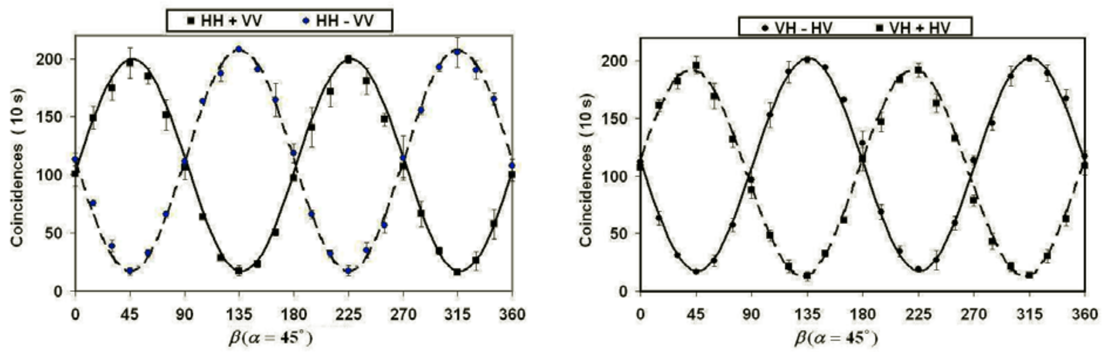


(a) (b)

Fig. 3. (a) Measurements of the polarization entanglement. The polarization analysis of photon 2 is varied, while that of photon 1 is at 45°. The rate at detector 2 (squares, right axis) is essentially constant; i.e., the photons are individually nearly unpolarized, while the coincidence rate (circles, left axis) displays the expected quantum-mechanical correlations. The solid curve is a best fit to Eq. (8), with visibility $V = 85.71 \pm 0.04\%$. Error bars indicate plus/minus one standard deviation statistical uncertainty. (b) Coincidences as the relative phase ϕ is varied by tilting the zero-order quartz wave plate just before the crystal; both photons are analyzed at 45°.

Fig. 3(a) shows data demonstrating the extremely high degree of polarization entanglement achievable with our source. The state is set to $\left(|H\rangle_s|H\rangle_i + |V\rangle_s|V\rangle_i\right)/\sqrt{2}$; the polarization analyzer in path A is set to 45°, and the other in path B is varied. As expected, the coincidence rate displays sinusoidal fringes with nearly perfect visibility (V = 85.71 ± 0.04% with ‘‘accidental’’ coincidences), while the singles rate is much flatter (V < 7.28 ± 0.09%).

To experimentally verify that we can set ϕ by changing the ellipticity of the pump light, the zero order quarter-wave plate before the crystals is tilted about its optic axis (oriented vertically), thereby varying the relative phase between horizontal and vertical polarization components. Fig. 3(b) shows the coincidence rate with both analyzers at 45°. For $\phi = 0, \pi$ the states $\left(|H\rangle_s|H\rangle_i \pm |V\rangle_s|V\rangle_i\right)/\sqrt{2}$ are produced. The other two Bell states $\left(|H\rangle_s|V\rangle_i \pm |V\rangle_s|H\rangle_i\right)/\sqrt{2}$ can be prepared simply by setting a half-wave plate in one of the arms at 45° to exchange H and V polarization.



(a) (b)

Fig. 4. Coincidence fringes for states (a) $\left(|H_sH\rangle_i \pm |V_sV_i\rangle\right)/\sqrt{2}$; (b) $\left(|V_sH_i\rangle \pm H_sV_i\right)/\sqrt{2}$.

Under these conditions, we attain a maximum coincidence fringe visibility (as polarizer B is rotated, with polarizer A fixes at 45°) of (87.58 ± 0.03)%, indicating the high quality of the source. Appropriately orienting the wave plates in path B, we produce all four Bell states and observe the expected correlations (Table I, Fig. 4).

The measured value of S is a figure of merit for the quality of the actual entangled state produced from the crystal. Therefore, for each of the four Bell states we took extensive data for the settings $\alpha = 0^\circ$, $\alpha' = 45^\circ$, $\beta = 22.5^\circ$, $\beta' = 67.5^\circ$; and $\alpha_\perp = 90^\circ$, $\alpha'_\perp = 135^\circ$, $\beta_\perp = 112.5^\circ$, $\beta'_\perp = 157.5^\circ$. The CHSH inequality was strongly violated in all cases; see Table I.

Table I. The four Bell states, the associated coincidence rate predictions, and the measured value of the parameter S.

Bell state	$N(\alpha,\beta)$	S
$\|\psi^{+}\rangle$	$\sin^2(\alpha+\beta)$	2.416 ± 0.077
$\|\psi^{-}\rangle$	$\sin^2(\alpha-\beta)$	-2.419 ± 0.078
$\|\phi^{+}\rangle$	$\cos^2(\alpha-\beta)$	2.409 ± 0.078
$\|\phi^{-}\rangle$	$\cos^2(\alpha+\beta)$	-2.407 ± 0.079

6. Conclusion

We have created pulsed polarization-entangled photon pairs, and use these in test of Bell inequality. The pulsed source of entangled photons uses a two-crystal geometry pumped by a violet diode laser operating in pulse mode, and can be tuned to produce any of all four Bell states. We obtain more than 85% visibility in all of four Bell states. We have shown a Bell inequality violation for these states of more than five standard deviations, in clear contradiction of local realistic hidden variable theories.

7. Acknowledgements

This work was supported by the Thailand Research Fund and the Kasetsart University Research and Development Institute.

References

[1] C. H. Bennett, P. W. Shore, IEEE Trans. Inf. Theory 44 (1998) 2724.
[2] Z. Y. Ou, L. Mandel, Phys. Rev. Lett. 61 (1988) 50.
[3] P.G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, Phys. Rev. Lett. 75(24)(1995) 4337.
[4] D. Dehlinger, M. W. Mitchell, Am. J. Phys. 70(9) (2002) 903.
[5] P. G. Kwiat, E. Waks, A. G. White, I. Appelbaum, P. H. Eberhard, Phys. Rev. A 60 (1999) R773.
[6] A. G. White, D. F. V. James, P. H. Eberhard, P. G. Kwiat, Phys. Rev. Lett. 83(16) (1999) 3103.
[7] D. Dehlinger, M. W. Mitchell, Am. J. Phys. 70(9) (2002) 898.
[8] J. F. Clauser, M. A. Horne, A. Shimony, R. A. Holt, Phys. Rev. Lett. 23(15)(1969) 880.